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Abstract—The quench behaviors of 10 model dipole magnets for the Superconducting Super Collider have been studied. Horizontally split yoke, vertically split yoke and the latest 50 *mm* diameter design were compared in the quench characteristics. The excitation results showed a good progress of the R&D program. SSC magnets can now be built with no training to the required field of 6.65 T at 4.3 *K*.

I. INTRODUCTION

Dipole magnets having a 6.65 T uniform field and a magnetic length of 15 *m* are the major component of the 20 TeV Superconducting Super Collider (SSC). Fermilab has been working on the R&D of the dipole magnet for the SSC in collaboration with SSCL and other high energy physics laboratories. This report describes the quench behavior of 1.5 m SSC model dipole magnets which have exactly the same cross-section as the SSC dipole magnet but a shorter length.

The magnet is a two-shell type cosθ design with wedges for high multipole compensation. Four Nb-Ti/Cu coils (inner and outer coils in upper and lower halves) are tightly clamped in a support structure of stainless steel collar laminations. The cold iron yoke outside the collars provides an additional mechanical support against deflection under excitation as well as field enhancement. The earlier models in this series had 40 *mm* aperture with the C358D cross section while the later models have 50 *mm* aperture with the W6733E cross section[1] in accordance with the recent design change of the SSC dipole magnet. The major difference between these two designs is the field quality improvement from the increase in the inner diameter. The change in conductor width provides an increase in current margin. The stiffness of the collars is also improved.

The Fermilab SSC magnet design[2,3,4] has some specific features. A vertically split yoke[5] was introduced to give better clamping of the coil than with a horizontally split yoke. The collars are keyed using the so called "square key method" in which the collars are compressed until the key can go in without large force. This method minimizes the scratching of the keys, thereby improving the dimensional and hence the field harmonics tolerances. The collar, key and tooling design allow also the use of the "tapered key method" in case the over-compression causes damage in the insulation material. Solid G10 spacers[3] are used in the ends of the coil. The inner to outer coil splice is made outside of the coil and the cable leading to the splice is preformed to the design shape and solder filled. The coil ends and splices are clamped by a 4-piece insulating collet and a tapered outer end can[4]. The materials of the can and collet pieces have a large influence upon the mechanical characteristics of the end through their thermal contraction coefficients. Design features of every tested magnet are listed in Table I.

II. MEASUREMENT

The magnets were tested in a 3.6 meter long vertical dewar located in the superconducting magnet R&D laboratory (Lab2) at Fermilab. The dewar was instrumented with pressure transducers and liquid helium level gauges. Temperature measurements were made by carbon and platinum thermometers attached to the shell of each magnet. By pumping the dewar, the temperature of the liquid helium bath can be lowered to ~3 *K*.

Table I. Tested Magnets [1]

Magnet	Dia. (*mm*)	Yoke Split	End Can	Collet Pieces
DS0308	40	Horiz.	S.Steel	G10‖
DS0309	40	Horiz.	S.Steel	G10‖
DS0310	40	Horiz.	S.Steel	G10‖
DS0311	40	Horiz.	S.Steel	G10‖
DS0313	40	Vert.	S.Steel	G10⊥
DS0314	40	Vert.	Aluminum	Stycast
DS0315	40	Vert.	Aluminum	Stycast
DSA321	50	Vert.	S.Steel	G10CR‖
DSA323	50	Vert.	S.Steel	G10CR‖
DSA324	50	Vert.	Aluminum	G10CR‖

[1] G10 with glass fibers in the radial direction (⊥) was used only in the return end of DS0313. The lead end remained the same as other magnets using azimuthal fibers (‖).

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Two TRANSREX 500-5 power supplies were used in parallel to supply current up to 12000 A at ramp rates of up to 400 A/sec. The inner cylinder of the warm bore, used for inserting magnetic field measuring probes, was evacuated during the quench tests to minimize the heat load on the coils. All instrumentation and power supplies are controlled and monitored by a MicroVAX 53 computer. Quench data are collected with four LeCroy 8212A fast data loggers on a CAMAC bus. The 40 mm SSC magnets are instrumented with 55 voltage taps for quench localization and the 50 mm magnets have 57 voltage taps. Voltage tap signals are sampled at a rate of 0.2 to 5 kHz. Fig.1 is an example of the voltage tap measurements. From the delay time between signals in various voltage taps, one can determine the quench location and the propagation velocity. The quench propagation velocity in these magnets was typically $\sim$ 75 m/sec. The magnets also had strain gauge pressure transducers to measure inner and outer coil stresses.

III. TRAINING BEHAVIOR

The quench performance of these magnets was generally very good. All the magnets went up to the conductor limited current which provides a field well above that required by the SSC. Most of the magnets showed only a few or no training quenches. Training histories are shown in Fig.2. Quench tests were performed at 4.3 K, 4.2 K, and then at 3.8 K. Quenches in Fig.2 are the results at 4.3 K except for DS0308 which was tested only at 4.2 K. The nominal ramp rate was 16 A/sec. The plateau (conductor limited) quenches are in the pole turn of the inner coils which has the highest magnetic field. The quench current and location of the quench origin are fairly stable after reaching

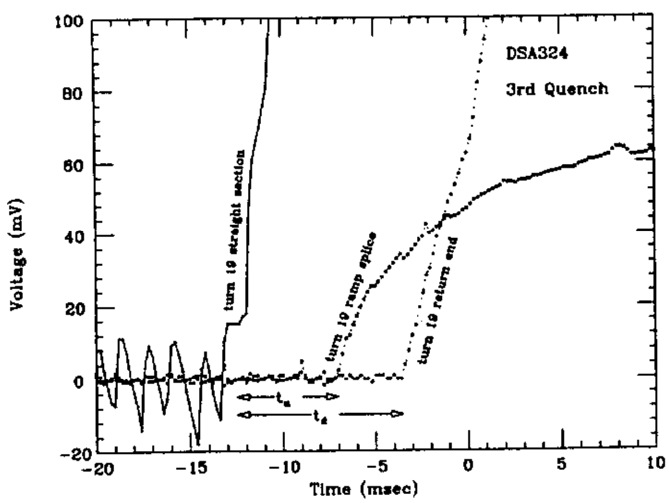

Fig.1: Quench Location and Velocity. Quench propagation time to up stream voltage tap, t_u, and time to down stream voltage tap, t_d, gives the velocity, v, by: $v = l/(t_d + t_u)$, where l is the distance between voltage taps which contains the quench origin. The quench origin is located at $lt_u/(t_u + t_d)$ from the upstream voltage tap.

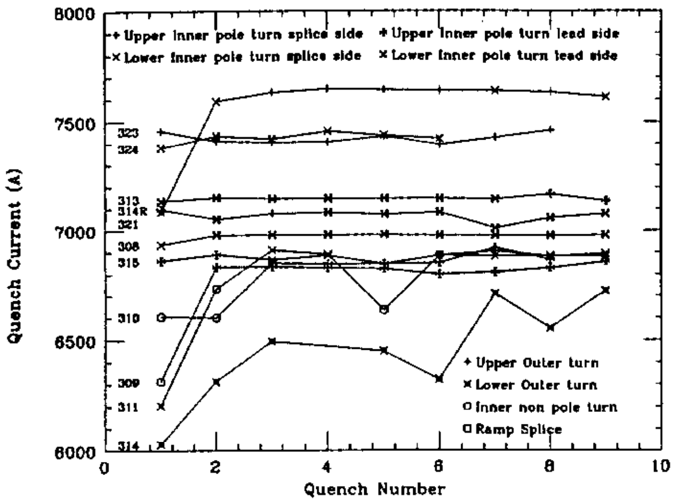

Fig.2: Training History of Quench Current

a plateau with a few exceptions. However, detailed observations of voltage tap signals sometimes shows that the quench origin moves around in that turn. The quench origin tends to be in the non-splice side in the 40 mm magnets and on the splice side in the 50 mm magnets. The direction of winding in 40 mm and 50 mm magnets are opposite but, because of the symmetry, there is no logical reason to account for this tendency. A thermal cycle (cycling the magnet from operating temperature to room temperature ten back to operating temperature) was done in most of the tests but usually there was no sign of significant retraining.

Magnet DS0308 was the first magnet in this series and had a very low pre-loading in the coil. The stress at the pole of the coil was observed to go to zero when it was excited. However, the magnet was not degraded in performance nor did it train with such a low pre-loading. The first quench was at 40 A below its plateau. The quench origin of this training quench was in tKe straight section of the pole turn of the lower inner coil. Since this magnet was tested at 4.2 K while others were tested at 4.3 K for the early quenches, good performance of this magnet might be partially due to the difference of the test temperature. Magnet DS0309 was assembled with increased pre-loading but had one training quench with a larger step than the previous magnet. The quench origin was in turn 10 (counting from the mid-plane) of the lower inner coil. The plateau quenches were in the lead side of the pole turn (turn 16) of the upper inner coil. Magnet DS0310 had two training quenches in upper inner coil turns 14 and 11. The rest were plateau quenches and were in the non-splice side of the upper inner coil at the pole turn. DS0311 had two training quenches one each in the lower outer coil and in turn 10 of the lower inner coil which is next to the wedge. It showed a drop in quench current in the 5th quench which occurred in the lead end of turn 10 of the upper inner coil.

DS0313, DS0314 and DS0315 are the 40 mm magnets with vertically split yokes. These magnets[6] essentially had no training. The mechanical stability of the vertically split magnet[7] seems to be effective to prevent the training in the mid-turns of the magnet[2]. DSA321, DSA323, DSA324 are 50 *mm* magnets[8] in the latest design. They all demonstrated good quench characteristics. The one training quench in DSA321 and a problem with DSA323 will be discussed in section VI.

IV. TEMPERATURE DEPENDENCE

The quench current of the magnet should follow the temperature dependence of the critical current, I_c, if there is no training involved. Therefore this is a convincing way to determine whether the magnet has reached the conductor limited current. The temperature dependence of the quench current, I_q, is related with temperature dependence of the I_c as:

$$\frac{dI_q}{dT} = \frac{1}{[1 - \frac{\partial I_c}{\partial H} F_t]} \frac{\partial I_c}{\partial T}$$

where F_t is the transfer function or the conversion ratio from current, I, to the magnetic field, H. Since $\frac{\partial I_c}{\partial H}$ is negative, the temperature dependence of quench current is smaller than that of the conductor I_c. Fig.3 shows the measured temperature dependence of the quench current. Quenches with ramp rates other than 16 A/sec and training quenches are excluded from the data. Fits to the data for each magnet give the temperature dependence of the quench current to be $17\%/K$ to $19\%/K$. The ramp rate dependence data in the following section are corrected by using experimental temperature dependences.

When the magnet is cooled to lower temperature, the increase of I_c should result in a higher quench current according to the equation above. Quenching with reduced temperature is a good test for the margin of mechanical stability. Some magnets showed more training at this stage. Fig. 4 shows the quench current observed when the temperature was reduced to 3.8 K after training was completed at 4.3 and 4.2 K. The magnets with horizontal split, DS0309, DS0310 and DS0311, continued to fluctuate with the quenches in the mid-turns as well as the pole turn. The change of current was not large but they took more than 5 quenches to reach the plateau at 3.8 K. The 40 *mm* magnets with vertically split yoke showed a little training, typically 1 or 2 quenches. The 50 *mm* magnets did not show any training even at 3.8 K. It would be necessary to reduce the temperature further to see the training in the 50 *mm* magnets. A quench test at 3.0 K was performed for DSA321 and the quench current reached 8959 A or about 8.8 T in the third quench.

V. RAMP RATE DEPENDENCE

Ramp rate dependence of the quench was studied for ramp rates up to 300 A/sec. (See Fig.5.) Although the required ramp rate of the SSC collider dipole magnet is less than $6A/sec$ the quench data at higher ramp rate is valuable information for the understanding of quench behavior. The measured temperature was 4.3 K and 4.2 K. Since there are fluctuations in the temperature, these data are corrected to $4.3K$ using the data described in the previous section.

The quench behavior from the view point of ramp rate dependence is categorized in a few groups. Differences among DS0308, DS0309, DS0311, DS0313 and DS0314 come from the conductor I_c. Their behaviors are essentially the same. These magnets showed about 5 A decrease of quench current for every $1A/sec$ increase above 100 A/sec. The quench locations in 40 *mm* magnets at high ramp rate are in the solder-filled cable at the inner-outer splice. One possible explanation would be the effect of eddy current heating in the solder of the splices. One exception in quench location is magnet DS0315 which did not show the effect of ramp rate until the ramp rate went over 200 A/sec. No ramp splice quenches were observed

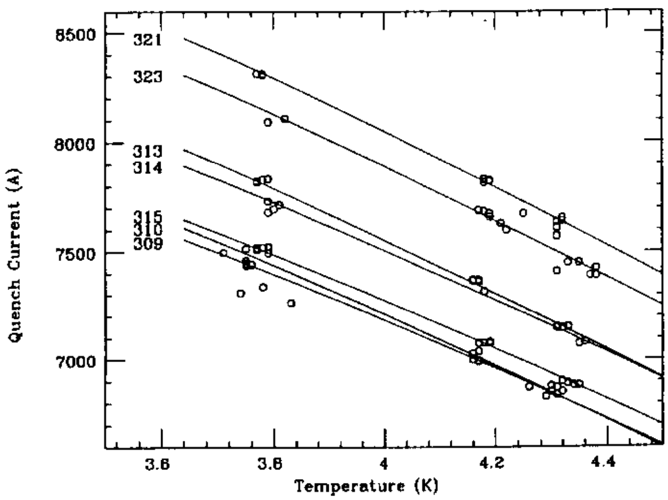

Fig.3: Temperature Dependence of Quench Current

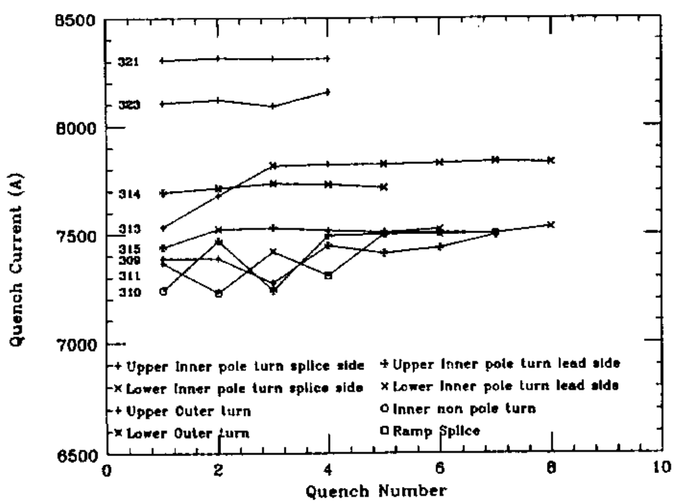

Fig.4: Training at 3.8 K

[2]DS0314 had a problem in the beginning but was fixed. Therefore, it is not counted as the essential training.

in this magnet. This magnet quenched in the outer coil very close to the splice, which is very unusual in this series of magnets. Since DS0315 has Stycast collet pieces and aluminum-alloy end cans, it could be because of better cooling at the end part; however, DS0314, which has the same end configuration, showed the same behavior as other magnets. There seems to be a threshhold in ramp rate for splice quenches to appear. The threshhold was 50 A/sec in DS0310 and 100 A/sec in most of other 40 mm magnets. Since 17% of Iq change corresponds to the temperature rise of 1 K from the results in the previous section, this threshhold could imply the temperature margin of 0.2 K for DS0310 and 0.4 K for other magnets at the ramp splice The reason why DS0310 and DS0315 behave differently is not clear at this time. The effect of the ramp rate on the 50 mm magnet quench is different from that of 40 mm magnets. The quench origin at high ramp rate is in the mid-turns rather than the splices. Eddy current heating in the wedge might be playing a role in this type of quench. The appearance of the effect seems to have no threshhold. Another point of interest in the 50 mm magnet quench is the difference in the magnitude of the effect which varies largely from magnet to magnet. DSA324 had larger prestress in the inner coil than the preceeding magnets.

VI. CAUSE OF QUENCHES

In general, it is very difficult to point out the cause of quenches because at high current close to I_c any small disturbance can trigger a quench. However, in some cases we have determined the causes of quenches. In the quench history shown in Fig.2, there are two lines for DS0314. The one which started quenching just above 6000 A was the training after first assembly. Inspection following partial disassembly of the end showed a gap between the spacer and the coil caused by excess epoxy which was applied to protect the voltage tap. After removing the epoxy clod, the magnet was reassembled and showed the very good performance indicated as 314R. Since this was the only magnet which showed more degradation than the SSC requirement, we should be able to trace the cause of the quench when it does not meet the design criteria. DSA321 had one training quench in the outer coil. The pressure measurement of the coil was effective to find that the pressure had changed through the training. The cause of the mechanical instability in this outer coil was believed to be that the brass shoe, which is a surface protection between the collar and the coil, was a little too short. DSA323 had the corrected length of brass shoe and did not show any training quenches. However, DSA323 made an occasional quench at the end part of the winding in the down ramp after many ramps of operation. Improper end preloading is under suspicion for the cause.

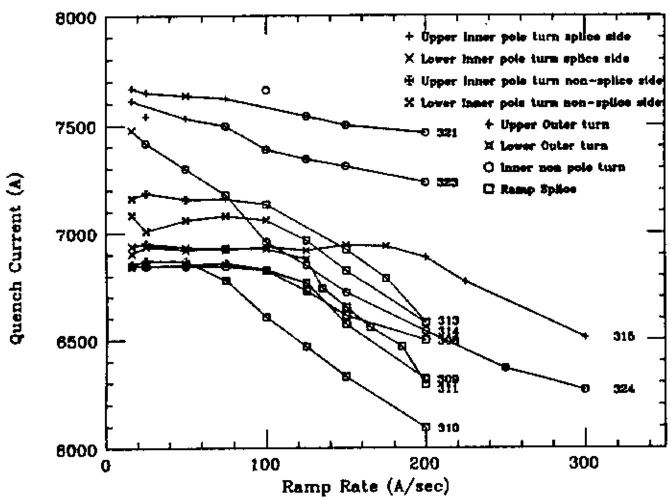

Fig.5: Ramp Rate Dependence of Quench Current

VII. CONCLUSION

Quench characteristics of the model dipole magnets were studied. The progress in the quench characteristics achieved through the R&D program was quite satisfactory. Magnets can be built and excited to the SSC required field with no training. Accidental training can be explained in their reason of occurrence and the recovery from the poor quench performance was achieved.

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